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COLLOIDS AND LIVING PHENOMENA

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IN recent years the colloids have assumed a great importance in all discussions of living matter, so much so that life has often been defined in terms of colloidal reactions. The protoplasm of the living organism consists essentially of (1) water, (2) crystalloids and (3) colloids, and it might be truly stated that all the complex and unintelligible manifestations of living matter depend, largely, on the delicate interplay of these three substances. Whether there is a vital force—an entelechy—a spirit that directs the wonderful behavior of these chemical combinations is a question which can not be conclusively answered. Certainly the results of physics, chemistry and biology within the last few years have tended to give a materialistic guidance to our conceptions of living phenomena, and many modern physiologists are in agreement with Verworn when he characterizes life as nothing more than a reaction of the proteids (colloids). In any event, it matters very little for this

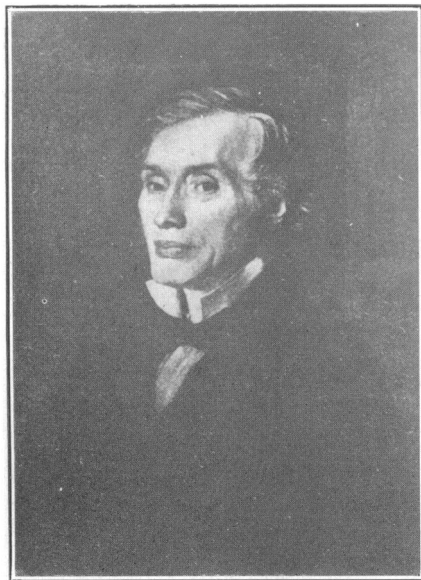


FIG. 1. THOMAS GRAHAM. (From Bayliss.)

discussion whether one's conception of life is "vitalistic" or "mechanistic." All that this paper wishes to present is the rôle played by the colloids in those unique reactions which are commonly designated as "living reactions," or as summed up in the term "life."

The colloids were first investigated by Thomas Graham (Fig. 1) in 1861, who applied the term to those substances which did not readily pass through a dialyzing membrane. To Graham the colloids and crystalloids represented two distinct worlds of matter with no transitions between them, and possessing the following well-defined properties:

Crystalloids

1. Are crystalline substances.
2. Form saturated solutions and crystallize out readily.
3. A saturation point is reached.
4. Are of low molecular weight.
5. Diffuse readily through animal membranes.

Examples of Crystalloids

Sugar, salts, fatty acids, amino-acids, glycerine, etc.

Colloids

1. Are amorphous substances.
2. Do not form saturated solutions and are not found to crystallize out from solution.
3. No saturation point is reached, the solution becomes thicker and thicker finally forming a viscid gum.
4. Are of very high molecular weight.
5. Diffuse but little or not at all through animal membranes.

Examples of Colloids

Gelatine, albumins, glue, gums, etc.

However, we now know that these are but arbitrary distinctions. While it is true that a substance in the colloidal state possesses wholly different properties than the substance in the crystalloidal state, yet it must be recognized that both are states of substances. Albumin, which exists as a colloid may, nevertheless, be obtained in a crystalline form and vice versa. Some of the commonest salts may form colloids. Thus sodium acetate possesses the qualities of a crystalloid in watery solution, while sodium stearate belongs to the colloids. Most of the typical colloids, like the proteids, may be broken down by the digestive ferments to form crystalloids. These ferments

break down the proteids into bodies intermediate between crystalloids and colloids. The proteoses, which are the first products in this metabolism, possess colloidal properties slightly less marked than the protein itself. The peptones, the next products in the breaking down process of protein, although not crystallizable, are, nevertheless, different from colloids and are true electrolytes. These are the steps that bridge the gap between colloids and crystalloids. Biochemists of to-day believe that many substances, perhaps all substances, may exist now in crystalloidal state and then in colloidal state.

This power of change from the colloidal to the crystalloidal state, and *vice versa*, seems to be the very essence of cell life. According to Wells:

We may look upon cell life as a constant attempt at the establishment of equilibrium, both chemical and osmotic, because the move toward one sort of equilibrium is always against the other. All the food-stuffs—fats, carbohydrates and proteins—are characterized by being colloids when intact and crystalloids when disintegrated, thus:

colloidal proteins \rightleftharpoons crystalloid amino acids,
colloidal glycogen \rightleftharpoons crystalloid sugar,
nondiffusible fats \rightleftharpoons diffusible soaps and glycerol.

In consequence of this, if the crystalloids diffuse from the blood into a cell there is at once an excess of this end of the equation, and hastened by the intracellular enzymes, synthesis to the colloid soon occurs to establish chemical equilibrium. Chemical changes in the crystalloids, by oxidation, reduction or hydrolysis, upset this chemical equilibrium and hence further diffusion, synthesis and hydrolysis continue, one upsetting the other continuously. If equilibrium were established we should have no further reactions, and the cells would be inactive. The constant upsetting of the equilibrium is what constitutes cell life.

Perhaps the most interesting characteristic of colloidal substances is their lability. They may readily be broken down and built up into other combinations. Moore in speaking of this lability of the colloids says:

The whole essence of the colloidal condition is that of a balance of play of energies in the most delicate equilibrium. All the known properties of colloids can be traced to feeble molecular affinities between the molecules themselves, causing them to unite into multi-molecules or "solution aggregates" and to balance between such affinities and similar feeble affinities for crystalloids in common solution with them, and for the molecules of the solvent.

Upon this lability depends the various phases undergone by the colloids in protoplasm.

Colloids are generally divided into the following phases, depending on their more liquid or jelly-like condition:

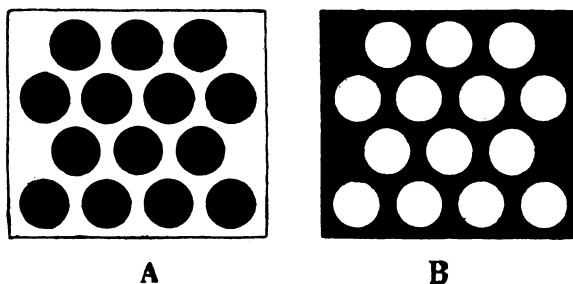


FIG. 2.. DIAGRAM ILLUSTRATING PHASES IN COLLOIDAL SYSTEMS. (After Bayliss.) If the black be regarded as solid phase and the white as the liquid phase, then *A* represents a hydrosol, whereas *B* represents a hydrogel.

I. *The Hydrosols* (dispersed states).—These are pseudo-solutions or fine suspensions. Fig. 2, *A*, represents the typical hydrosol condition.

II. *The Hydrogels* (undispersed states).—These may be either (*a*) the emulsion type, or (*b*) the coagulated or precipitated type (mixtures of emulsions). Fig. 2, *B*, represents the typical hydrogel condition.

In hydrosols the colloidal particles (or multi-molecules) are free and invisible. Each particle is distinctly separated from every other particle and behaves as a single unit or mole-

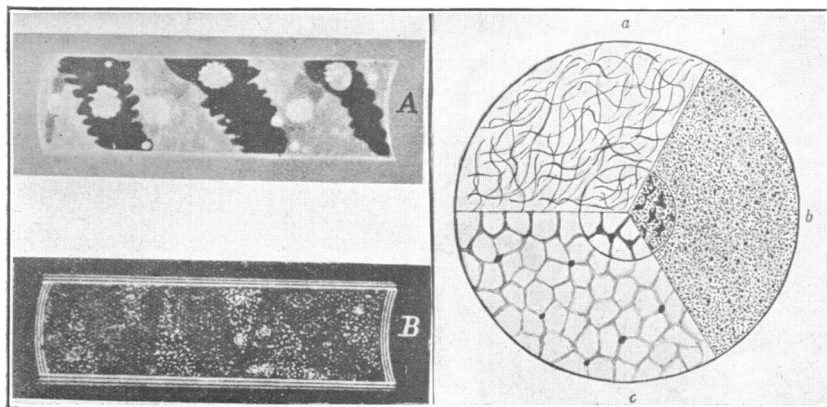


FIG. 3. CELL OF *Spirogyra*. (From Bayliss, after Gaidukov.) *A*, under ordinary microscope; *B*, under ultra-microscope.

FIG. 4. DIAGRAM ILLUSTRATING THE APPEARANCE OF PROTOPLASM WITHIN THE CELL. (After Bailey.) *a*, fibrillar structure of protoplasm; *b*, granular structure of protoplasm; *c*, foam or emulsion structure of protoplasm.

cule in solution. The particles of the colloids do not enter into true solutions, but usually exist in the form of suspensions which exhibit Brownian movement. This can be clearly seen when colloidal solutions are examined with the ultra-micro-

scope. Figs. 3, B and 5, *a-e* show the appearance of the suspended colloidal particles in the living cells of *Spirogyra* and of the dog's nervous system as seen under the ultra-microscope.

We know that most colloids form suspensions only from still another line of evidence. Substances which enter into true solution alter the freezing point as well as the boiling point of the solvent, but colloids change these points very little if at all.

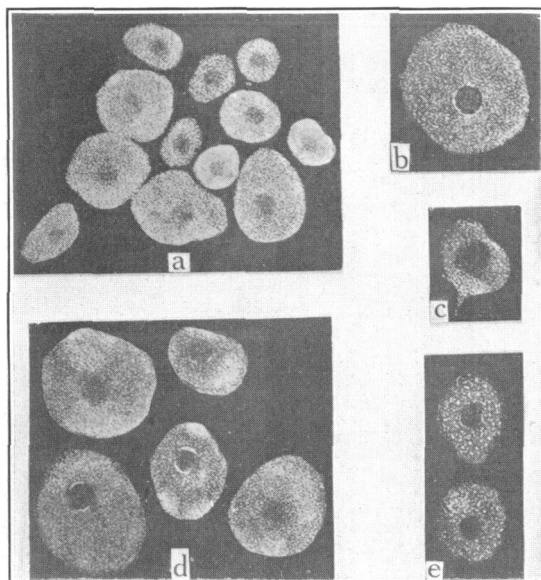


FIG. 5 (*a-e*). LIVING NERVE CELLS FROM THE DORSAL ROOT GANGLIA OF THE DOG AS SEEN WITH THE ULTRA-MICROSCOPE. The colloidal particles within the cells exhibit Brownian movements. (From Bayliss, after Marinesco.)

Furthermore, true solutions, such as formed by crystalloids, exert an osmotic pressure while suspensions show no such behavior. Typical colloids do not exert osmotic pressure, hence form no real solutions.

Some colloids, however, have been recently shown to form real solutions; for instance, Starling has shown that the proteins dissolved in the blood serum possess an osmotic pressure, hence they form true solutions. Pfeffer has also shown by his experiments on gum arabic and glue that these colloids exert osmotic pressure, therefore forming real solutions.

When, for some cause or another, such as a change in the environment of the hydrosol, the multi-molecules of the colloid are aggregated together, a hydrogel is produced. In this condition we have a diphasic system of the colloid, consisting of (1) a very dilute solution of the smaller multi-molecules, and (2) a

more or less solid of huge molecular complexes of the colloid containing comparatively little of the solvent. In forming the hydrogel there has occurred more or less of a setting of the solid colloidal particles.

When this setting of the colloidal particles has occurred in spherules far apart and separated by the fluid medium, then an emulsion is produced. If the setting continues, then a meshwork of the solid particles may be formed, enclosing the liquid phase. In this way a foam or reticulum may be produced, and the meshwork may take on many forms.

It is thus evident that in this manner the various structures found in living cells, foam structures, granular structures, networks, spindle fibers, chromosomes and the like may originate.

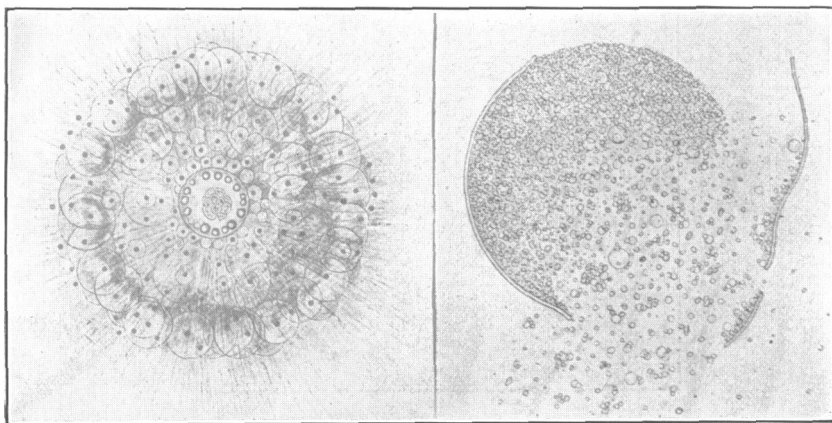


FIG. 6. THE RADIOLARIAN *Thalassicolla pelagica* HAECKEL, showing the foamy, emulsion-like character of the protoplasm. (From Doflein, after R. Hertwig.)

FIG. 7. THE EMULSION-LIKE APPEARANCE OF THE PROTOPLASM OF A RUPTURED OVUM OF *Fucus*. (After Seifriz.)

Fig. 4 illustrates the various appearances which the protoplasm of the cell may assume.

Colloidal gels are of two kinds, (1) reversible, and (2) irreversible.

A reversible gel is one in which a reversal of the condition that produced gelation causes it to return to its original state, the sol state. For example, when gelatin in the hydrosol condition is cooled it solidifies and assumes the hydrogel condition. Upon heating this hydrogel it will again assume the hydrosol condition.

On the other hand, an irreversible gel is one in which a reversal of the condition that produced gelation does not cause the colloid to return to its original condition. For instance,

when the albumen of the white of egg is heated it solidifies and assumes a gel condition. When this gel is cooled it remains unchanged and never reverts to its original hydrosol condition.

All living matter is characterized by its richness in colloids of the emulsion type (Figs. 6 and 7) which present a remarkable degree of reversibility. Protoplasm is really an aggregate of colloids holding water for the most part, in which are con-

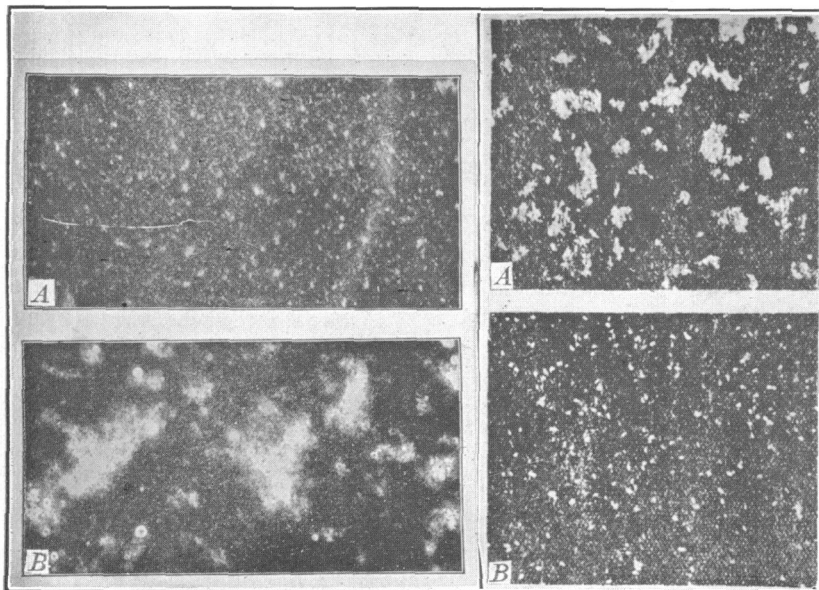


FIG. 8, A and B. TWO STAGES IN THE CLOTING OF CASEIN, showing the aggregation of the finer colloidal particles of A into the coarser clumps shown in B. (From Mathews after Stubel.)

FIG. 9, A and B. AGGREGATION BY ELECTROLYTES OF THE BLOOD CORPUSCLES OF THE FISH *Scyllium canicula*, suspended in half-normal sodium chloride. (From Bayliss after Mines.) A, effect of addition of 0.0008 molar cerium chloride; B, effect of addition of 0.08 molar cerium chloride. The dilute solution causes aggregation by reversing the sign of the charge (from negative to positive), of a part of the corpuscles. The concentrated solution causes a rapid reversal of all the corpuscles from negative to the positive sign, causing them to remain suspended.

tained electrolytes and non-electrolytes. Hence, the chemical reactions of protoplasm occur in dilute solutions of electrolytes.

Electrolytes when in solution dissociate into ions, the positive ions, or *cations*, bearing positive charges of electricity, while the negative ions, or *anions*, bear negative charges of electricity. Thus when NaCl is dissolved in water, a dissociation of the Na and Cl ions occurs. The Na ions bear positive charges while the Cl ions bear negative charges. The Na ions are therefore *cations*, whereas, the Cl ions are the *anions*. Within recent years it has been found that ions may exist not

only as charged atoms, but as charged groups of atoms (radicals) as well.

Many biochemists and physiologists now believe that the physiological action of many substances depends upon the electrical charges borne by the ionized particles, and not on the chemical nature of the particles themselves.

Colloidal particles have been shown to bear electrical charges. The colloid particle, although consisting of many atoms, behaves as a single charged particle as far as its electrical charge is concerned. In general acid colloidal particles are electro-negative and alkaline colloidal particles are electro-positive. The charged particles induce the opposite charge in the surrounding water or other fluid medium in which they are suspended. If the colloidal particles are charged with positive electricity, the surrounding fluid medium is charged negatively and vice versa. Also, the number of charges in the surrounding fluid is proportional to the surface of the colloidal particle. If by any means (such as heat, electricity, internal chemical changes, etc.), the colloidal particles are thrown together into aggregations, then a reduction in the amount of surface of the particles occurs, bringing about a readjustment in the electrical conditions of the surrounding medium. Conversely, when a change occurs in the electrical state of the medium surrounding the colloidal particles, a readjustment in the latter occurs. For instance, when the density of the charge of particles is diminished aggregation leading to coagulation (Fig. 8, A and B) is brought about; when the density of the charge is increased a still finer division of the particles is produced (Fig. 9, A and B). Either change might occur as a result of the chemical changes in the particles themselves or in the conditions surrounding them.

Hardy has made a very extensive study of the electrical properties of colloids. Guyer summarizes Hardy's work as follows:

Hardy, using a sol of proteid has shown: (1) that a gel is produced by the addition of electrolytes, but not by the addition of non-electrolytes unless they act chemically; (2) that the gelation produced by electrolytes is due to the electric charge carried by the ion, inasmuch as identical results follow the use of an electric current from a battery; (3) that the signs of the electric charges carried by the ions (plus or minus) determine the movements of colloidal particles either keeping them in suspension as a sol or causing them to fall into the gel condition (*e. g.*, a sol having its colloidal particles negatively charged will pass into a gel state if plus ions are added or if the plus electrode of a battery be introduced).

Certain daily events may be interpreted intelligently by bearing in mind the above facts. For instance, the irritability

of the human organism depends largely on the state of the colloids in the nervous system. When these colloids go into a gel condition the individual becomes irritable. When this condition is prevented irritability is lost. To take concrete examples:

1. *Mechanical stimulation* such as a shock, push, blow or electrical stimulation would cause neighboring colloidal particles on which they acted to coalesce, thus reducing their surface. Since the colloidal particles are normally positively charged, they induce the negative charge in the surrounding medium. Any reduction in the surface of the colloidal particles releases a portion of the negative charges previously induced in the fluid medium. These released negative charges act on the neighboring colloidal particles, etc. Thus a wave of gelation results, passing over the nerve, with the liberation of negative ions at the end of the process which call the muscles into play, resulting in action.

2. *Stimulation by Light and Ether Vibrations.*—Protoplasm is stimulated by light due to the charges of the electrons in the sun. When these electrons move through the ether they set up vibrations which, when they come in contact with protoplasm, act like ions, setting up a wave of gelation over the colloids in nerves, thereby bringing about a response.

3. *Chemical Stimulation.*—The action of certain chemicals, like chloroform, ether and alcohol on protoplasm may be explained on a similar basis. These substances increase the hydrosol condition, thereby preventing irritability. So long as these drugs are administered the colloidal particles of the nervous system are divided more finely, thereby causing a loss of consciousness. When these substances wear off consciousness returns. The above explains the values of ether and chloroform as anesthetics. The action of alcohol or whiskey during a snake bite may also be explained on the same grounds. Snake poison causes a coagulation of the colloidal particles. Alcohol prevents such precipitation.

On such a basis we can readily understand the rapid changes in the consistency of protoplasm—changes from more rigid conditions to those that are more fluid and vice versa. Only by understanding the reactions of the three substances entering into living combinations, namely, water, crystalloids, and colloids, can we hope to intelligently comprehend such living processes as metabolism, growth, irritability and the like. In a word "life or the life process is a reaction of the colloids," and in order to understand life or the life process the biologist of to-day must give his moments to the study of the colloids.